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Analysis of different models to estimate energy savings related to windows in residential buildings

M.K. Urbikain *, J.M. Sala

Department of Thermal Engineering, School of Engineering of Bilbao, The University of the Basque Country, Spain

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A B S T R A C T

A Window Energy Rating System (WERS) provides a simple, approximate method to compare the energy performance of the various windows and to determine the different potential savings for the various weather conditions. The main aim of this paper is to obtain a WERS for two climatic zones in Spain.

For this purpose, the heating loads and energy savings of a residential building with different types of windows were obtained by three ways. Firstly, the energy through the window was evaluated considering only the climatic conditions. Secondly, the study was performed taking into account the energy useful for the heating system considering the climate and the type of building. Finally, the different cases were simulated using TRNSYS16 and WINDOW5. This study was performed for different European climates.

The WERS proposed here is based on the second method. It takes into account the *U* factor of the window, *U* factor of the frame, absortivity of the frame, solar heat gain of the glazing and infiltration.

1. Introduction

Building energy demand represents about 41% of all energy consumed in the European Union. Energy certification of the different parts of a building can be a useful tool to improve the energy performance of the construction as a whole.

Windows play an important role in the energy performance and, therefore, should be chosen carefully.

Defining a Window Energy Rating System is not a simple problem because window performance depends on the climate where the window will be used, the type of building and the orientation.

Therefore, the rating will not be an absolute indicator of the energy performance of the window. In fact, performance can vary according to several factors and it is difficult to generalize because of the number of factors involved (climate, type of enclosures, internal loads, infiltration, ventilation, etc.). Nevertheless, a rating system will allow various windows to be compared under the same conditions.

The idea of a rating system is being applied in several countries, where different approaches to the problem have been taken. The NFRC system [1] considers the window properties, thermal transmittance (*U*-value), solar heat gain coefficient (SHGC), visible light transmittance (VT) and air leakage (AL). The English model [2] uses these properties for the window, combined into a single equation. The Danish model [3,4] uses the *U*-value and *g*-value of the glazing, combining them into a single equation obtained from the energy balance, considering a distribution of windows in a single family house. In addition to this indicator, this model also uses the *U*-value of the frame, multiplied by the design width of the frame, and the linear thermal transmittance of the glazing edge in order to rate window according to energy performance. In Italy, efforts have also been made to develop an energy rating system [5].

Total heat flow through a window consists of the flow of heat losses or gains, which depends only on the temperature difference between the two sides, a gain due to incident solar radiation, and losses due to leakage through cracks. Other added complications are that the *g*-value of the glazing varies according to the angle of incidence and this dependence is different for each type. Air leakage actually accounts for only a small percentage of the conduction losses: 1–5% in standard windows and higher in thermally efficient windows, 3–9%.

The first part of this research consisted of comparing different methods to obtain energy gain or losses due to windows by applying them to a building for different climatic zones. The second was to propose a Window Energy Rating System (WERS) that would be indicative of window performance for residential buildings in the Basque Country.

2. Net energy gain through the window

The heat flow through a window can be basically described by the thermal transmittance (*U*-value), total solar energy transmittance (*g*-value), and air leakage (*L*). Conduction losses per unit area

* Corresponding author.
E-mail address: mirenkarmele.urbicain@ehu.es (M.K. Urbikain).

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Nomenclature

a	parameter in angle-dependence formula for the g-value
A	coefficient in energy balance formula (kWh/m^2)
A_T	total window area (m^2)
A_{TOT}	total building envelope area (m^2)
b	parameter in angle-dependence formula for the g-value
B	coefficient in energy balance formula (kWKh/m^2)
c	parameter in angle-dependence formula for the g-value
c_p	specific heat (kJ/(kg K))
C	coefficient in energy balance formula (h/m^3) (kWh/m^2)
D	coefficient in energy balance formula (kKh)
f_s	stack coefficient (l/s)^2/(cm^4 K)
f_w	local wind coefficient (l/s)^2/((cm^4) (m/s)^2)
F	solar heat gain coefficient of the window
F_0	solar heat gain coefficient of the window at normal incidence
g_0	g-value of the glazing at normal incidence
g	g-value of the glazing
h_e	external surface heat transfer coefficient (W/(m^2 K))
h_{fg}	latent heat of vapor at the considered air temperature (kJ/kg)
I_G	global radiation (kWh/m^2)
I_b	beam radiation (kWh/m^2)
$I_{diff,sky}$	diffuse radiation reflected by sky (kWh/m^2)
$I_{ref,ground}$	diffuse radiation reflected by ground (kWh/m^2)
K_{TOT}	building heat loss coefficient (kW/K)
L_{75}	window leakage at a pressure difference of 75 Pa and outdoor temperature difference of 20 °C (m^3/h)
n	number of air changes per hour (1/h)
PF/20	pressure factor for conversion coefficient
p	number of panes
q	category parameter
q_c	heat losses due to temperature difference per unit area (kWh/m^2)
q_s	heat gain from solar radiation per unit area (kWh/m^2)
q_{as}	rate of energy consumption due to sensible heating or cooling for the incoming air (kWh/m^2)
q_{al}	rate of energy consumption due to latent heating or cooling for the incoming air (kWh/m^2)
Q	airflow rate (m^3/s)
Q_{int}	heat gains from internal sources (kWh)
$Q_{sol,u}$	useful solar heat gain for building-heating system (kWh)
$R_{f,sol}$	solar reflectance of outer surface of glazing system
$R_{b,sol}$	solar reflectance of inner surface of glazing system
$S_g(T_b)$	cumulative radiation up to temperature T_b (kWh/m^2)
t	time (h)
T_b	balance temperature (°C)
T_{int}	indoor temperature (°C)
T_{ext}	outdoor temperature (°C)
T_{sol}	solar transmittance of glazing
T_{vis}	visible transmittance of the window
$T_{vis,g}$	visible transmittance of glazing
ΔT	temperature interval (K)
Δt	time interval (h)
U_T	U-value or thermal transmittance of the window (W/m^2 K)
U_f	thermal transmittance of the frame (W/m^2 K)
U_{TOT}	total thermal transmittance of the building (W/m^2 K)
U_g	U-value or thermal transmittance of glazing (W/m^2 K)
v_{wind}	wind speed (m/s)
V	volume of enclosed air (m^3)
x	humidity ratio of air (mass water/mass dry air kg/kg)

Greek symbol

α_1	absorptance of the first pane in glazing system
α_2	absorptance of the second pane in glazing system
α_3	absorptance of the third pane in glazing system, if any
α_f	absorptivity of the frame
α	parameter in angle-dependence formula for the g-value
β	parameter in angle-dependence formula for the g-value
γ	parameter in angle-dependence formula for the g-value
η	annual fuel utilization efficiency
ρ	air density (kg/m^3)
θ	angle of incidence of direct radiation
$\theta_{eq,sky}$	equivalent angle of incidence of diffuse radiation reflected by sky
$\theta_{eq,ground}$	equivalent angle of incidence of diffuse radiation reflected by ground

are due to the difference between the indoor and outdoor temperatures

$$q_c = \sum U_T \cdot \Delta T \cdot \Delta t \tag{1}$$

where U_T is the thermal transmittance of the window (W/m^2 K), ΔT the temperature difference (K), and Δt is the time interval (h) wherein the sum is extended over the year (or the heating season).

The g-value allows solar heat gain to be calculated. The Meteonorm software [6] provides values for horizontal global radiation, diffuse horizontal radiation, and outdoor temperatures for various locations. Radiation levels at the vertical surface are then obtained for the different orientations, using the radiation levels at the horizontal surface. Radiation on a tilted surface has three radiation components: beam, diffuse and diffuse reflected by the ground [7]. Diffuse radiation from the sky and radiation reflected by the ground will be treated as beam radiation with equivalent angles of incidence. Therefore, the heat gain due to solar radiation is as follows

$$q_s = \sum F \cdot I_G \cdot \Delta t \tag{2}$$

where F is the solar heat gain coefficient of the window (dimensionless) and I_G is the global radiation (kW/m^2).

Air leakage increases the thermal load of a building in three ways. First, the incoming air must be heated or cooled to the indoor air temperature. Therefore, the energy consumption due to this sensible heat is given by

$$q_{as} = \sum Q \cdot \rho \cdot c_p \cdot \Delta T \cdot \Delta t \tag{3}$$

where Q is airflow rate (m^3/s), ρ the air density (kg/m^3) and c_p is the air specific heat (kJ/(kg K)).

Additionally, incoming air changes the moisture content of the air in the building. In some cases, incoming air should be dehumidified during the summer or humidified in the winter. The energy consumption due to this latent load is as follows

$$q_{al} = \sum Q \cdot \rho \cdot h_{fg} \cdot \Delta x \cdot \Delta t \tag{4}$$

where h_{fg} is the latent heat of vapor at the considered air temperature (kJ/kg) and Δx is the difference between the humidity ratio of indoor air and the humidity ratio of outdoor air (kg/kg).

Finally, air leakage can diminish the performance of building enclosures, and heat flow may be greater than the initially estimated. This last effect is difficult to quantify. The meteorological data of wind velocities and outdoor humidity used in this study have been provided by the Spanish National Institute of Meteorology (INM).

3. Angle-dependence of the total solar energy transmittance

The solar heat gain given by Eq. (2) is harder to deal with, because the g-value for the glazing varies with the angle of incidence of the radiation. It is important to take this dependence into account, because more than half the incident sunlight on a window for a country in southern Europe occurs at angles above 50° for a window facing the south. Therefore, it is necessary to describe this dependence at high angles of incidence as precisely as possible.

This angle-dependence is different for the various kinds of glazing systems. Empirical formulas are used most often and there are different models (e.g., clear glass, tangent, polynomial, bulk). Two models have been used in this study: the tangent model and the polynomial model.

The tangent model is defined by the following equation

$$g = g_0 \cdot \left(1 - \tan^x\left(\frac{\theta}{2}\right)\right) \tag{5}$$

wherein x is equal to 4 for most glazing systems.

The polynomial model [8] does not take into account the influence of the glass and coating thicknesses and the glass absorptance, but does consider the number of panes and type of coating, in other words, the g-value will depend on the value at normal incidence, g_0, the number of panes (p), and a category parameter (q) that depends on the type of coating. These values have been tabulated for various kinds of coatings by Karlsson et al. The polynomial model is given by the following expression

$$g = g(g(0), p, q) = g_0 \cdot (1 - a \cdot z^{\alpha} - b \cdot z^{\beta} - c \cdot z^{\gamma}) \tag{6}$$

wherein

$$z = \frac{\theta}{90} \tag{6.1}$$

$$a = 8; b = \frac{0.25}{q}; c = (1 - a - b) \tag{6.2}$$

$$\alpha = 5.2 + 0.7 \cdot q; \beta = 2; \gamma = (5.26 + 0.06 \cdot p) + (0.73 + 0.04 \cdot p) \cdot q \tag{6.3}$$

4. Window energy rating models

Three types of window energy rating models have been used:

Method 1: In addition to taking the physical parameters of the glazing into consideration (U_g, g_0), this model considers the weather conditions [9] and is based on a simple formula that includes the degree-days or degree-hours and the weighted total solar radiation throughout the heating season, which is variable for each orientation.

Method 2: This model takes the building type into account using a parameter that considers building characteristics such as the type of enclosures, internal loads, infiltration, ventilation, and occupancy schemes. A similar equation to the above is obtained as a result, but with a distinction made between the total solar heat gains and the useful solar heat gains for the building [10].

Method 3: This model consists of a detailed simulation of a building with the various types of windows. This approach is the most precise way to calculate the energy savings, but also requires detailed information on the building and some user experience with the software [11].

To perform the comparison, glazing, windows, and the building described in Sections 5 and 6, respectively, have been considered.

4.1. Method 1: net energy balance through the window, taking weather conditions into account

Energy gain or loss through the glazing system (per unit area) for the heating season is expressed as follows

$$E = A \cdot g_0 - D \cdot U_g \tag{7}$$

wherein:

$$A = \sum\left(I_b \cdot \left(1 - \tan^4\left(\frac{\theta}{2}\right)\right) + I_{diff,sky} \cdot \left(1 - \tan^4\left(\frac{\theta_{eq,sky}}{2}\right)\right) + I_{ref,ground} \cdot \left(1 - \tan^4\left(\frac{\theta_{eq,ground}}{2}\right)\right) \cdot \Delta t\,(kWh/m^2)\right) \tag{7.1}$$

if the tangent model is used. I_b is the beam radiation (kW/m^2), $I_{diff,sky}$ the diffuse radiation reflected by the sky (kW/m^2). $I_{ref,ground}$ the diffuse radiation reflected by the ground (kW/m^2), θ the angle of incidence of beam radiation. $\theta_{eq,sky}$ the equivalent angle of incidence of diffuse radiation reflected by the sky and $\theta_{eq,ground}$ is the equivalent angle of incidence of diffuse radiation reflected by the ground

or

$$A = \sum\left(I_b \cdot \left(1 - a \cdot \left(\frac{\theta}{90}\right)^{\alpha} - b \cdot \left(\frac{\theta}{90}\right)^{\beta} - c \cdot \left(\frac{\theta}{90}\right)^{\gamma}\right) + \left(1 - a \cdot \left(\frac{\theta_{eq,sky}}{90}\right)^{\alpha} - b \cdot \left(\frac{\theta_{eq,sky}}{90}\right)^{\beta} - c \cdot \left(\frac{\theta_{eq,sky}}{90}\right)^{\gamma}\right) \cdot \sum I_{diff,sky} + \left(1 - a \cdot \left(\frac{\theta_{eq,ground}}{90}\right)^{\alpha} - b \cdot \left(\frac{\theta_{eq,ground}}{90}\right)^{\beta} - c \cdot \left(\frac{\theta_{eq,ground}}{90}\right)^{\gamma}\right) \cdot \sum I_{ref,ground}\right) \cdot \Delta t\,(kWh/m^2) \tag{7.2}$$

if the polynomial model is used, and

$$D = \sum(293 - T_{ext}) \cdot \Delta t\,(kKh) \tag{7.3}$$

where T_{ext} is the outdoor temperature (K), assuming a constant indoor temperature of 293 K.

The frame absorptivity α_f and the frame U-value U_f should be considered in order to take the frame effect into account. The frame total solar energy transmittance is calculated as $U_f \cdot \alpha_f/(h_e \cdot A_s/A_f)$ wherein h_e is the external surface heat transfer coefficient and A_s/A_f is the developed surface to frame area that has been taken equal to one. Therefore, the energy absorbed by the frame and reemitted inwards is $I_G \cdot U_f \cdot \alpha_f/h_e$. The last term in expression (8) takes air infiltration into account. The use of Eq. (7) for the entire window assembly (i.e., including the frame) yields the following equation:

$$E = A \cdot g_0 + B \cdot \alpha_f \cdot U_f - D \cdot U_T - C \cdot L_{75} \quad (8)$$

wherein A and D are the parameters defined above.

L_{75} is window infiltration rate under a pressure difference of 75 Pa ($m^3/(hm^2)$).

B is given by

$$B = \sum I_G \cdot \frac{\Delta t}{h_e} \,(\text{kKh}) \quad (8.1)$$

where the external heat transfer coefficient is equal to 23 W/(m^2 K).

C is expressed as

$$C = \sum \frac{\text{PF}}{20} \cdot \frac{1.2}{3600} \cdot \frac{1000}{1000} \cdot (T_{\text{int}} - T_{\text{ext}}) \cdot \Delta t + \sum \frac{\text{PF}}{20} \cdot \frac{1.2}{3600} \cdot 2340 \cdot \Delta x \cdot \Delta t \,(\text{kWh h/m}^3) \quad (8.2)$$

wherein 1.2 is the density of air (kg/m^3), 3600 a conversion factor to transform h to s, PF/20 a conversion factor to transform the infiltration rate at 75 Pa to an infiltration for a pressure difference closer to what is found in residential buildings (dimensionless), 1000 the air specific heat (J/(kgK)) and 2340 is the latent heat of vapor at the considered air temperature (kJ/kg).

The PF pressure factor is based on the Lawrence Berkeley National Laboratory (LBNL) model [12] which divides the problem into two parts. On the one hand, there is a wind regimen where the dynamic pressure dominates the infiltration and on the other, a stack regime where the temperature difference has the most influence on the problem. This factor is given by

$$\text{PF} = 10 \cdot [f_s \cdot (T_{\text{int}} - T_{\text{ext}}) + f_w \cdot v_{\text{wind}}^2]^{1/2} \quad (8.3)$$

where v_{wind} is the wind velocity (m/s), f_s the stack coefficient $(l/s)^2/(cm^4\,K)$ and f_w is the local wind coefficient $(l/s)^2/((cm^4)(m/s)^2)$.

The stack factor, f_s, depends on the number of building stories. The wind factor, f_w, depends on how protected the building is and on the number of building stories [13].

4.2. Method 2: net energy balance through the window, taking into account the weather conditions and building type

Along with the weather conditions, Model 2 also takes the building type into consideration. The same equation is used, but the balance temperature T_b is also introduced as a characteristic parameter of the building. T_b is defined as the mean outdoor temperature above which heating of the building is no longer required, or the outdoor temperature for which, given a specific indoor temperature, total heat losses are equal to the sum of heat gain due to solar radiation, occupancy, lighting, and equipment [13]. The balance temperature plays an equivalent role to the utilization factor [14,15]. The balance temperature is expressed as

$$T_b = T_{\text{int}} - \frac{(Q_{\text{sol,u}} + Q_{\text{int}})}{(K_{\text{TOT}} \cdot \Delta\tau)} \quad (9)$$

wherein $$K_{\text{TOT}} = \sum (U_{\text{TOT}} \cdot A_{\text{TOT}} + V \cdot c_p \cdot n) \quad (9.1)$$

$\Delta\tau$ is the period considered, which may be the heating season or a month, Q_{int} are the heat gains from internal sources (kWh), K_{TOT} the heat loss coefficient (kW/K), sum of the transmission heat loss coefficient and the ventilation heat loss coefficient, U_{TOT} the thermal transmittance of the building (W/(m^2 K)). A_{TOT} the windows' area (m^2), V the volume of enclosed air (m^3) and n is the number of air changes per hour (1/h).

$Q_{\text{sol,.u}}$ is the useful solar heat gain through the glazing, i.e., heat gain up to temperature T_b. An iterative process is required to calculate these gains, solving Eqs. (9) and (10) at the same time.

$$Q_{\text{sol,u}} = S_g(T_b) \cdot A_g \quad (10)$$

wherein S_g (T_b) is the cumulative radiation up to temperature T_b (kWh/m^2) and A_g is the glazing area (m^2).

Therefore, the following equation will be used in the type 3 analysis

$$E = \sum \frac{(A' \cdot g_0 + B' \cdot \alpha_f \cdot U_f - D' \cdot U_T - C \cdot L_{75})}{\eta} \quad (11)$$

if $T_{\text{ext}} < T_b$.

wherein A', B' and D' have the same expressions as A, B, and C, but calculating the sum only when $T_{\text{ext}} < T_b$. A parameter τ, related to the time constant of the building, is used to take the building inertia effect into account. This time interval can be defined as the time the indoor temperature takes to drop 2 °C or 3 °C. Karlsson et al. [10] give approximate values of this parameter for buildings of light, medium and heavy construction. Therefore, the energy gained through the window over 1 year is

$$E = \sum \frac{(A' \cdot g_0 + B' \cdot \alpha_f \cdot U_f - D' \cdot U_T - C \cdot L_{75})}{\eta} \quad (12)$$

if $T_\tau < T_b$.

where η is the Annual Fuel Utilization Efficiency.

4.3. Method 3: detailed simulation with TRNSYS

TRNSYS 16 was used for building modeling introducing multi-layer walls, occupancy loads, lighting, equipment, and leakage, in addition to the occupancy patterns and WINDOWS 5 [16] for window modeling.

TRNSYS is a dynamic simulation program for thermal systems created by the Solar Energy Laboratory of the University of Wisconsin. Type 56 is the multizone model used to simulate the residential building. This allows a file containing the optical and thermal data and the thermal and solar properties of windows to be imported from WINDOW software for inclusion in type 56. The program is based on the star network method [17].

5. Reference building and locations

Due to the fact that the main purpose of this work has been to obtain a Window Energy Rating System to be applied in residential buildings in the Basque Country, a real apartment building has been taken as the reference. This building is an example of the building general trend in the last years. This study assumed an occupancy level of 1 person per 30 m^2 with a gain of 65 W for sensible heat and 55 W for latent heat per person. A lighting power of 5 W/m^2 and an equipment load of 4.4 W/m^2 have been used. The occupancy, lighting, and equipment schemes are those considered in the Spanish Building Code [18].

The Spanish Building Code divides Spain in 12 different climatic zones, with a letter to characterize winter and a number to characterize summer. Bilbao and Vitoria correspond to the two climatic zones C1 and D1 [18]. Previously to establish a WERS, different methods of estimating energy gains or losses due to windows have been compared. Two additional European cities with temperate and cold climate, London and Copenhagen have been studied to check that the three methods can be applied to different climates.

Two window to wall area ratio have been taken and are shown in Table 1. The first one is the original distribution of windows in the building. Due to the fact that the glazing area has an influence on energy demand, a second distribution has been studied in order to check the similarity of the results using the three methods when

Table 1
Window distribution in the residential building.

Orientation	Distribution of windows no. 1	Distribution of windows no. 2
North	15.3	24.0
South	22.2	32.4
East	18.6	26.2
West	21.2	30.5

the glazing area is increased. Therefore, the window area in the second distribution has been increased from 40 to 60% in the different orientations, achieving window to wall ratios of 20–30% that can be considered typical of our country.

6. Types of glazing and windows

To compare the different methods, the glazing systems shown in Table 2 were used. Type 1 is normal double-glazing, used as the reference glazing for the comparisons. Type 2 is a low-*E* double-glazing with high solar gain and type 3 is the same type, but with argon in the cavity. Type 4 is a low-*E* glass with a lower emissivity than type 2 (0.155), resulting in a lower *U*-value. Type 5 is similar to this, but with argon instead of air in the cavity. Type 6 is a solar control, low-*E* double-glazing and type 7 is a spectrally selective, low-*E* glazing with a visible-to-solar ratio of 1.8. Type 8 is triple glazing with two low-*E* coatings and argon in the two cavities. Type 9 is a version of type 6 in which the argon gas has been replaced with krypton, whereas type 10 is triple glazing with two low-*E* coatings and krypton in the cavities.

The thermal, solar and optical properties of the various types of glazing are shown in Tables 3 and 4, where U_g is the thermal transmittance, g_0 the solar heat gain coefficient at normal incidence, $T_{vis,g}$ the visible transmittance, T_{sol} the solar transmittance, $R_{f,sol}$ the solar reflectivity of the outer face of the outer pane, $R_{b,sol}$ the solar reflectivity of the inner face of the innermost pane and α_1, α_2, and α_3 the absorptivities for each pane in the system of glazing.

Windows 1–9 have a PVC frame with a thermal transmittance of 1.7 W/(m^2 K). Window 10 has a special PVC frame with a *U*-value of 1 W/(m^2 K). Windows 6–9 have triple glazing. Table 5 shows the *U* factor, solar heat gain coefficient F_0 and visible transmittance T_{vis} for the window.

When the tangent and polynomial models presented above are applied, the *g*-value for the different angles of incidence and types of glazing is obtained. The largest discrepancies appear at angles higher than 50°, as shown in Fig. 1.

7. Energy saved according to window type. Comparison of different methods

As mentioned in previous sections, the three methods to obtain heating energy saved according to the window type have been compared. A shading factor of 0.7 [14] is used for type 1. Figs. 2 and 3 show the savings per m^2 of window and year obtained for the building and windows described in the above sections for the building located in Bilbao and London. The same comparison was done for Vitoria and Copenhagen. The type 1 window is taken as a reference. For the locations of London and Copenhagen, glazing type 6 and type 7 have not been taken into account.

The method 1 can only be used as a qualitative approach because the results obtained by this method and by the detailed simulation are very different, even though the trends remain the same in all cases.

Table 2
Types of glazing.

	Number of panes	Coating position	Coating emissivity	Gas fill
Type 1	Double	None		Air
Type 2	Double	Surface 3	0.299	Air
Type 3	Double	Surface 3	0.299	Argon
Type 4	Double	Surface 3	0.155	Air
Type 5	Double	Surface 3	0.155	Argon
Type 6	Double	Surface 2	0.094	Air
Type 7	Double	Surface 2	0.033	Air
Type 8	Triple	Surfaces 2,5	0.155	Argon
Type 9	Triple	Surfaces 2,5	0.155	Krypton
Type 10	Triple	Surfaces 2,5	0.066	Krypton

Table 3
Thermal, solar, and optical properties of glazing.

	U_g	g_0	$T_{vis,g}$
Type 1	2.8	0.780	0.812
Type 2	2.13	0.733	0.747
Type 3	1.9	0.736	0.747
Type 4	1.86	0.722	0.742
Type 5	1.56	0.726	0.742
Type 6	1.71	0.348	0.453
Type 7	1.57	0.374	0.677
Type 8	0.89	0.559	0.620
Type 9	0.74	0.559	0.620
Type 10	0.55	0.487	0.697

Table 4
Optical properties of glazing.

	T_{sol}	$R_{f,sol}$	$R_{b,sol}$	α_1	α_2	α_3
Type 1	0.720	0.128	0.128	0.086	0.066	
Type 2	0.613	0.152	0.134	0.088	0.147	
Type 3	0.613	0.152	0.134	0.088	0.147	
Type 4	0.579	0.160	0.141	0.089	0.172	
Type 5	0.579	0.160	0.141	0.089	0.172	
Type 6	0.270	0.231	0.329	0.481	0.019	
Type 7	0.317	0.292	0.389	0.376	0.016	
Type 8	0.427	0.178	0.178	0.239	0.055	0.102
Type 9	0.427	0.178	0.178	0.239	0.055	0.102
Type 10	0.397	0.325	0.325	0.163	0.057	0.059

Table 5
Thermal, solar, and optical properties of windows.

	U_T	F_0	T_{vis}
Type 1	2.69	0.648	0.650
Type 2	2.17	0.610	0.598
Type 3	1.99	0.612	0.598
Type 4	1.98	0.601	0.595
Type 5	1.76	0.604	0.595
Type 6	1.88	0.301	0.363
Type 7	1.77	0.322	0.543
Type 8	1.30	0.471	0.497
Type 9	1.18	0.470	0.497
Type 10	0.92	0.414	0.583

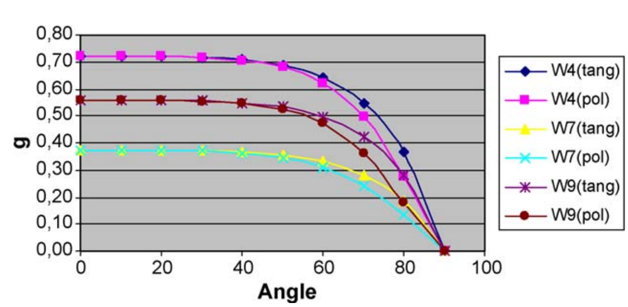

Fig. 1. Angular dependence for the different glazing using the two models.

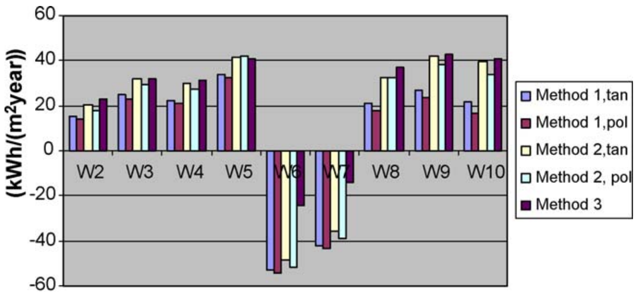

Fig. 2. Energy saved for the building located in Bilbao, taking window 1 as the reference case.

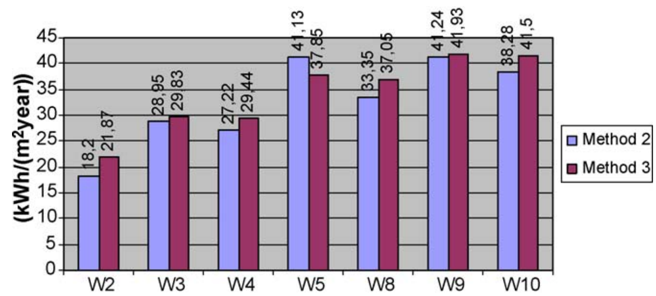

Fig. 4. Heating energy saved in Bilbao with the second distribution of windows.

The method 2 and in particular the one that uses the tangent angle-dependence model, predicts energy savings close to those obtained with TRNSYS. The results obtained with this software should be more accurate because the building is simulated with the actual walls, taking into account the people, equipment and lighting schedules in the heating period. The building is divided in thermal zones and the star method is used to analyze the convective and radiant heat fluxes between surfaces and the air. The Transfer Function Coefficients are also used to describe the conductive transitory heat flux through walls. Therefore, this is taken as the reference method.

The method 2 has been chosen because it is sufficiently precise to have a quantitative idea of the energy savings and it allows a simple way to establish a dependence law of the useful energy for the heating system of the building in terms of the window U factor, the frame U factor, the solar heat gain and the infiltration rate.

The tangent dependence has been selected from the practical point of view. The polynomial model requires the knowledge of the category q, that depends on the type of coating, thick film of tin oxide, thin films of silver, ... and this information is not always easily found.

Method 3 is more precise but it proves more difficult to find a dependence law of the energy savings in terms of the U factor, g-value, frame U factor, frame absortivity and infiltration because of the number of parameters involved in the simulation.

Once the model has been selected for window characterization (method 2 with tangent g dependence), the distribution of windows in the building under consideration was modified to use the window to wall ratio no. 2, Table 1. The calculation was performed for Bilbao, Vitoria and Copenhagen. The results obtained for the various types of windows are shown in Figs. 4 and 5 for Bilbao and London respectively. The saving trends when changing from one type of glazing to another are maintained using the two methods.

The results obtained for the cities analyzed using method 2 are similar to those from method 3 for the cases of low-E double and triple glazing. However, the losses obtained by the simplified method are higher than those obtained using the detailed simulation method for the cases of solar control or spectrally selective glazing for the building located in Bilbao and Vitoria. Nevertheless, it is unlikely to use solar control windows for residential buildings in these regions.

In general, it is proved that double-glazing with a low-emissivity coating and high solar heat gain is very appropriate in temperate and cold climates. Window type 5, double-glazing with a low-emissivity coating and low conductivity gas in the cavity or type 4 double-glazing with low-emissivity are the most energy efficient in Bilbao and Vitoria. Type 5 would save 41 kWh/(m^2 year) in Bilbao and 66 kWh/(m^2 year) in Vitoria. Type 4 would save 30 kWh/(m^2 year) in Bilbao and 50 kWh/(m^2 year) in Vitoria.

Type 5 was not effective from the economic point of view in Bilbao and in Vitoria. The useful life of the windows was considered to be 30 years, and an interest of 6% was supposed. The price per kWh for heat produced with natural gas was assumed to be 0.03 €. However, type 4 is cost effective in Vitoria for the two distribution of windows (with a benefit of 0.35 €/(m^2 year) for the first window to wall ratio and 0.29 €/(m^2 year) for the second distribution of windows).

Double-glazing with a low-emissivity coating and Ar in the cavity is also very interesting in London, Fig. 3. It means an energy benefit of 86 kWh/(m^2 year) comparing with a double-glazing. Triple glazing entails higher benefits in London than in Bilbao or Vitoria. Type 5 window continues to be very beneficial in Copenhague with a saving of 105 kWh/(m^2 year). Triple glazing involves a greater energy saving in cold regions than in temperate regions.

Figs. 4 and 5 were presented to check that increasing the window area considerably in every orientation, the saving differences were similar. For instance, the type 4 implies a saving of 31 kWh/(m^2 year) in Bilbao and 50 kWh/(m^2 year) in Vitoria with the distribution of windows no. 1. It is obtained a saving of 29 and 48 kWh/(m^2 year) with the distribution of windows no. 2 in Bilbao and Vitoria respectively.

When increasing the window to wall ratio, the differences in London and Copenhagen are higher due to the bigger difference between the inside and outside temperatures. For example, it is

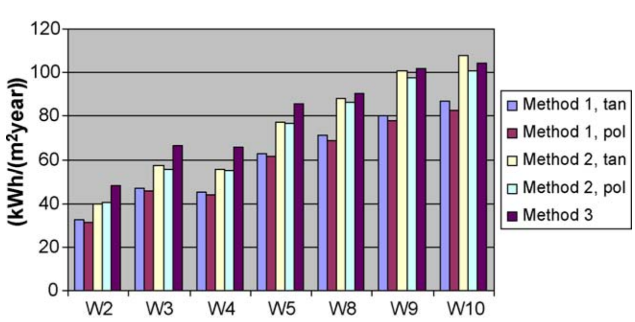

Fig. 3. Energy saved for the building located in London, taking window 1 as the reference case.

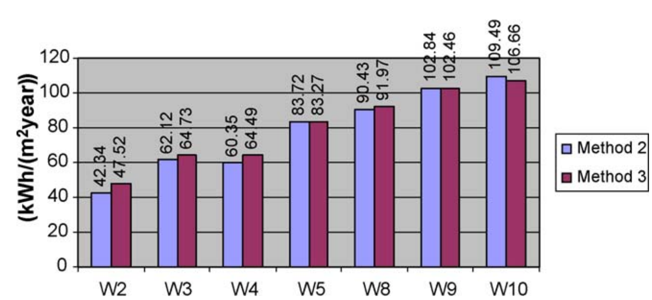

Fig. 5. Heating energy saved in London with the second distribution of windows.

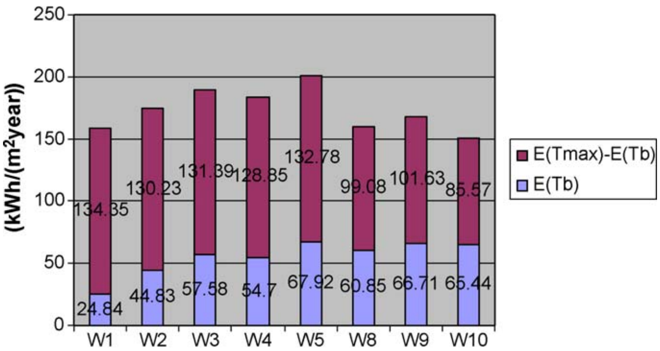

Fig. 6. Useful solar heat gain for the different kinds of glazing in the case of the building in Bilbao.

found a saving of 66 kWh/(m^2 year) when using a type 4 window with the window percentage no. 1 and 60 kWh/(m^2 year) with the window percentage no. 2 in London. In Copenhagen the difference is more remarkable, with a saving of 81 kWh/(m^2 year) with the first distribution of windows and 73 kWh/(m^2 year) with the second one.

This seems to indicate that the influence of the glazing area is more significant in cold climates than in temperate climates. However, the increase of the window area in all the orientations involves similar savings for the simulated building in our region.

In order to apply the method 2 it is important to know the balance temperature which can vary according to parameters such as enclosures, internal loads, infiltration, ventilation and glazing type. The balance temperature was found to be around 13 °C in Copenhagen, 13.5 °C in London, 14.7 °C in Bilbao and 13.6 °C in Vitoria, for the building analyzed. This method also provides information on which part of the energy flow coming through the window is useful for the heating system. Figs. 6 and 7 show the useful solar heat gains for the cases of Bilbao and Vitoria. Analyzing the relation $E(T_b)/(E(T_{max}) - E(T_b))$ it can be seen that low-emissivity glazing is more interesting in Vitoria that in Bilbao. For example, glazing type 4 has a relative value of $E(T_b)/(E(T_{max}) - E(T_b))$ of 34% and 30% in Vitoria and Bilbao respectively. However, window type 1 is more useful in Bilbao (16%) that in Vitoria (8%).

8. Window energy rating certification

Energy performance in buildings can be encouraged through two mechanisms: (1) regulations intended to limit energy use of buildings and (2) certification which seeks better energy performance than that reflected by the regulations through the use of energy rating systems. These systems should provide clear information on the energy performance of the product, whether the building as a whole or the window as in our case.

Several countries already have a Window Energy Rating System for their weather conditions; a case in point would be Denmark. In the Danish case, a window energy rating from *A* to *C* is obtained using *U*-value and *g*-value of the glazing and the values of the linear thermal transmittance ψ and the *U*-value of the frame.

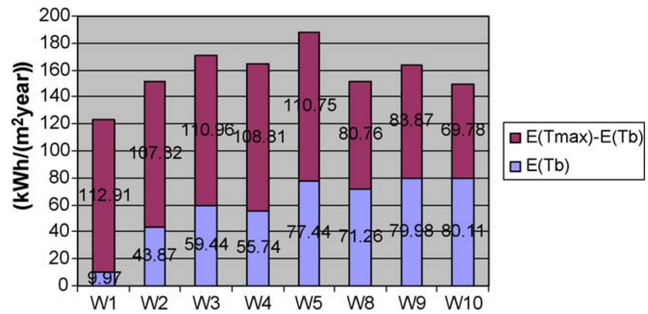

Fig. 7. Useful solar heat gain for the different kinds of glazing in the case of the building in Vitoria.

The annual gain per m^2 obtained by simplified method 2, Eq. (12), is proposed as an energy rating for a window. For each of the four orientations for the climatic zones of Bilbao (C1) and Vitoria (D1), the expressions shown in Table 6 are obtained. These equations should be used in case of using different kinds of windows in the various orientations.

Taking an average for the percentage of window to wall area in the building under consideration yields the last expression in Table 6 for the climatic zones of the Basque Country. This equation should be used when using the same windows in all the directions. If there are shade components it would be necessary to multiply the dependent part of solar radiation by the shading factor to obtain the relative savings of using one type of glazing over another.

Lastly, a window energy rating has been established as shown in Table 7. A total of 36 different windows were considered in order to establish the scale. The expressions of Table 6 were evaluated taking different frames (aluminium with thermal break, PVC and wooden frames), different frames absortivities and different kinds of glazing (double-glazing, low-emissivity double-glazing, double-glazing with low conductivity gas in the cavity, triple glazing, etc.). This scale has been set up to distinguish between efficient windows and windows that are not. A Class E window would not be efficient and, therefore, it would not be logical for windows below Class D to be used in new buildings.

An energy saving and ecological approach has been followed, not an economic approach.

It has been taken a PVC frame and double-glazing window as the reference case, with a rating *D*. Inefficient windows are those with a value of the energy index below the reference case (rating *E*). Windows that represent more than 35 kWh/(m^2 year) with respect to the same reference are classified as B or A. They use to be wooden or PVC frame and double low-emissivity glazing windows that work very well in our climate. Windows classified as C have an intermediate behavior between the reference and those classified as B and A.

Figs. 8 and 9 indicate the cumulative frequencies for the cases of Bilbao and Vitoria. These figures have been built taken into account the windows considered to stablish the energy index. The Primary Energy Savings due to windows using the expressions of Table 6 has been represented in abcissa .The cumulative frequency of windows (percentage) has been drawn in ordinate. The figures

Table 6
Energy balance equation through the window.

	Climatic zone C1 (kWh/m^2)	Climatic zone D1 (kWh/m^2)
North	$120.92g_0 + 1.36\alpha_f U_f - 67.13U_T - 0.75L_{75}$	$148.92g_0 + 1.68\alpha_f U_f - 95.83U_T - 1.10L_{75}$
South	$410.40g_0 + 4.47\alpha_f U_f - 67.13U_T - 0.60L_{75}$	$535.00g_0 + 5.82\alpha_f U_f - 95.83U_T - 0.93L_{75}$
East	$284.24g_0 + 3.14\alpha_f U_f - 67.13U_T - 0.63L_{75}$	$377.62g_0 + 4.15\alpha_f U_f - 95.83U_T - 0.96L_{75}$
West	$212.53g_0 + 2.37\alpha_f U_f - 67.13U_T - 0.60L_{75}$	$271.93g_0 + 3.02\alpha_f U_f - 95.83U_T - 0.93L_{75}$
Average	$236.73g_0 + 2.24\alpha_f U_f - 65.76U_T - 0.63L_{75}$	$330.10g_0 + 3.08\alpha_f U_f - 95.33U_T - 0.96L_{75}$

Table 7
Window energy rating for the climatic zones C1 and D1.

Class	E (kWh/m^2) C1	E (kWh/m^2) D1
A	$E > 50$	$E > 65$
B	$35 < E < 50$	$42 < E < 65$
C	$24 < E < 35$	$26 < E < 42$
D	$-15 < E < 24$	$-32 < E < 26$
E	$E < 0$	$E < -32$

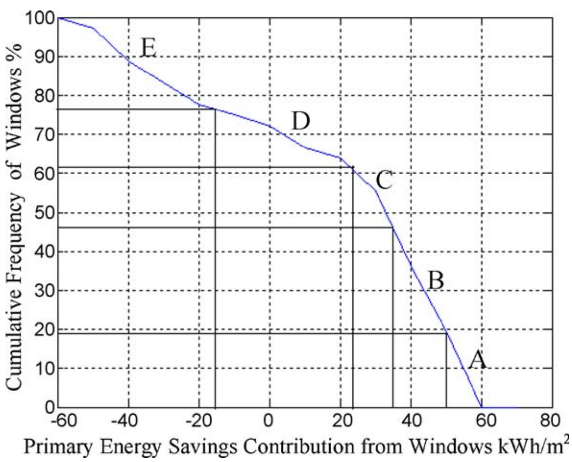

Fig. 8. Cumulative frequency plot for the climatic zone C1.

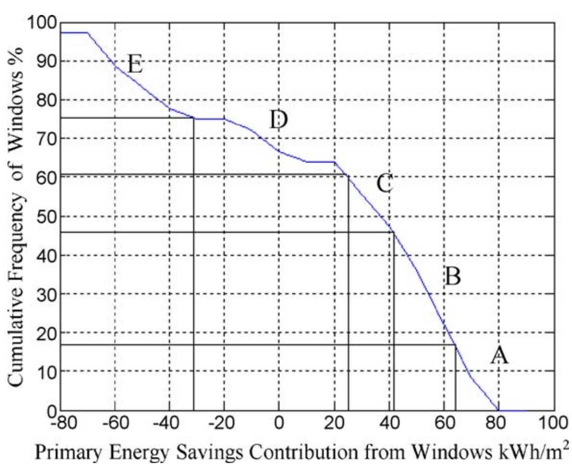

Fig. 9. Cumulative frequency plot for the climatic zone D1.

show the graphical representation of the last expression in Table 6. This indicates that from the selected windows population,the 20% will be A windows, the 25% B, 15% C, 15% D and 25% E approximately.

The thresholds of the classes have been defined such that, although the solar gain is different for the same window according to climatic zone, it can generally achieve the same energy rating in both climate zones, despite the different contributions to energy saving. The use of a Class C versus Class D window would signify a 10% decrease in energy consumption levels and, therefore, CO_2 emissions. Using Class B glazing instead of Class C or Class A instead of Class B would mean a decrease above 5%.

9. Conclusions

Three types of methods to define a window energy rating system for different climates in Europe were analyzed. In method 1, an energy balance through the window that included the frame effect was carried out. The same energy balance was performed in method 2 but assuming that only part of this solar radiation is used by the heating system, considering the balance temperature. Method 3 was a dynamic simulation of the building, according to the Seem star network method and was used as the reference method.

In the three cases the trends in heating savings were maintained as the window is changed. Method 1 is too simple to predict heating savings in the actual building. Model 2 predicts energy savings closer to the simulation results, except in the case of solar control or spectrally selective glazing. However, it is unlikely to use solar control glazing in residential buildings in these regions. The methods were applied to different locations and to different window to wall ratio in order to check the similarities of the energy saving results, when these parameters changed. The method 2 was chosen to build a Window Energy Rating System because it is accurate enough to approximately predict energy savings and it allows a simple way to establish a dependence law of the useful energy for the heating system of the building in terms of the total U factor, the frame U factor, the g-value and the infiltration rate. Moreover, this method can give an idea of how useful a type of glazing for a climate is and the proportion between the useful solar heat gain and the total solar heat gain through the window $E(T_b)/(E(T_{max}) - E(T_b))$.

Finally, a Window Energy Rating System was proposed for residential buildings in the Basque Country, expressed at kWh/(m^2 year), using method 2 for the calculation. This takes into account the solar gain that is essential from the building-heating standpoint. Therefore, different windows can be compared and their relative heating energy savings for a reference building can be estimated using a simple equation. This rating was establish from an energy saving and ecological point of view, not with an economic criteria and it allows the window rating in *A*, *B*, *C*, *D* and *E*, depending on the value of the energy index.

Acknowledgements

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